

**MARS EXPLORATION ROVER FIELD OBSERVATIONS OF IMPACT CRATERS AT GUSEV CRATER AND MERIDIANI PLANUM AND IMPLICATIONS FOR CLIMATE CHANGE.** M. Golombek<sup>1</sup> J. A. Grant<sup>2</sup>, L. S. Crumpler<sup>3</sup>, A. F. C. Haldemann<sup>1</sup> and the Athena Science Team. <sup>1</sup>Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, <sup>2</sup>Smithsonian Institution, Washington, D.C. 20560, <sup>3</sup>New Mexico Museum of Natural History and Science, Albuquerque, NM 87104.

**Introduction:** The Mars Exploration Rovers have provided a field geologist's perspective of impact craters in various states of degradation along their traverses at Gusev crater and Meridiani Planum. This abstract will describe the craters observed and changes to the craters that constrain the erosion rates and the climate [1]. Changes to craters on the plains of Gusev argue for a dry and desiccating environment since the Late Hesperian in contrast to the wet and likely warm environment in the Late Noachian at Meridiani in which the sulfate evaporites were deposited in salt-water playas or sabkhas.

**Gusev Plains:** Spirit has traversed a generally low relief somewhat rocky plain dominated by shallow circular depressions called hollows. Hollows are typically 1-20 m in diameter (the smallest observed is 0.4 m), generally have rocky rims characterized by angular and fractured blocks, and smooth soil filled centers. Perched, fractured and split rocks are more numerous around hollows than elsewhere and redder rocks are common near eolian drifts [2]. Hollow morphology and size-frequency distribution strongly argue that they are impact craters rapidly filled in by eolian material. Excavation during impact would deposit ejecta with widely varying grain sizes, which would be in disequilibrium with the eolian regime. This would lead to deflation of ejected fines, exposing fractured rocks, and creating a population of perched coarser fragments. Transported fines would be rapidly trapped within the depressions creating the hollows [2].

Many of the rocks at Gusev show evidence for partial or complete burial, followed by exhumation [2, 5]. These include two-toned rocks with a redder patination along their bases, ventifacts that originate from a common horizon above the soil (suggesting that the lower part of the rock was shielded), rocks that appear to be perched on top of other rocks, and some undercut rocks, in which the soil has been removed from their bases. These observations suggest that surface deflation, perhaps highly localized, of 5 to 60 cm has occurred.

Four craters >90 m in diameter, Bonneville, Missoula, Lahontan, and an un-named crater located to the west of Lahontan, were visited by Spirit. Only Bonneville is relatively fresh. The others have been largely filled in by sediment with diameters of 160 m, 90 m, and 100 m and depths of 3-4 m, 4 m and <1 m, respectively.

**Bonneville Crater:** Several lines of evidence suggest Bonneville is a relatively fresh crater that was

formed into unconsolidated blocky debris [2]. The largest rock increases from 0.5 m to ~1 m to ~2.5 m diameter as the rock abundance increases by a factor of 4-6 from the discontinuous ejecta, through the continuous ejecta to the rim, suggesting a relatively pristine ejecta blanket with a sharp, easily mapped edge. Although the crater is shallow (~10 m deep) the rubble walls show no signs of mass wasting and eolian material deposited inside is limited to 1-2 m thickness by protruding boulders. The low depth to diameter ratio of Bonneville and other small craters in and on its walls suggest that they formed as secondary craters [3, 4].

**Meridiani Planum:** Far fewer craters have been found by Opportunity at Meridiani Planum due to its relatively young Late Amazonian surface age [6]. A clear progression in the state of modification of the craters by eolian erosion and infilling can be seen in the roughly 10 craters from ~10 m to 150 m in diameter that have been characterized by Opportunity. All of the craters impacted into Late Noachian light toned sulfate rich sedimentary evaporites (exposed in their rims and/or walls).

Three impact craters that were characterized well during the nominal mission are Endurance, Eagle, and Fram, which are 150 m, 20 m and 10 m in diameter and 21 m, 3 m, and 1 m deep, respectively. Fram appears freshest with ejecta blocks on the surface, Endurance retains steep interior walls, and Eagle appears the most degraded with a highly modified shallow sand and granule filled interior.

After Endurance, craters that Opportunity has characterized well prior to arriving in the etched terrain are Naturaliste, Geographe, Vostok, Vega, Viking, and Voyager, which are 11 m, 6.5 m, 50 m, 8 m, 18 m and 18 m in diameter and 2.5 m, 1 m, <1 m, ~0.5 m, 1.5 m, and ~1 m deep, respectively. Two other craters, Jason and Alvin (both ~11 m diameter) were imaged from farther away, but appear similar to Eagle. The smallest craters observed by either rover are 20 cm and 10 cm in diameter (~1 cm and <1cm deep) imaged by Opportunity on sol 433 on the sand, suggesting they are very young.

The freshest craters observed are Vega and Viking, which have ejecta blocks on the surface, blocky raised rims and what appears to be only thin sand in their interiors. Slightly more degraded craters are Fram, Naturaliste, Geographe, and Voyager, which have blocky rims, more sand filled interiors and ejecta blocks on the plain, some of which have been eroded down or planed off even with the sand. Endurance is more degraded with a raised rim, backwasted upper slopes, some sand inside,

but no ejecta on the surface (completely eroded away). Eagle, Jason and Alvin are more eroded with more sand filled interiors, eroded rims with some exposed outcrop, but no ejecta. Vostok is the most eroded example as it shows up a ring of light outcrops that have been planed off by the sand sheet with a subdued <1 m central depression (no ejecta or raised rim). Depth diameter ratios and estimates of material filling the craters suggests most are primaries, except for Fram, Vega, Viking, Voyager and the 10 and 20 cm diameter craters, which have low depth/diameter ratios implying they may be secondaries.

**Deflation and Erosion Rates:** The observed deflation of the cratered plains surface at Gusev is a measure of the cumulative change of the surface since the Hesperian [7]. The gradation and deflation of ejected fines of 5-60 cm and deposition in craters to form hollows thus provides an estimate of the average rate of erosion or redistribution via the vertical removal of material per unit time typically measured on Earth in Bubnoff units (1 B = 1  $\mu\text{m}/\text{yr}$ ) [8, 9]. The deflation and exhumation of rocks at Gusev suggest of order 10 cm average deflation or redistribution of the site. Deflation and redistribution of a single layer of fines about 10 cm thick would also fill all the hollows and craters. Over the age of the cratered plains (Late Hesperian/Early Amazonian or ~3 Ga [10]) this argues for extremely slow average erosion rates of order 0.1 nm/yr or  $10^{-4}$  B. Such erosion rates fall between those estimated in a similar manner at the Mars Pathfinder landing site (~0.01 nm/yr) [11] and at the Viking Lander 1 site (~1 nm/yr) [12] and argue for very little net change of the surface implying a dry and desiccating environment similar to today's has been active throughout the Hesperian and Amazonian or since ~3.7 Ga [10].

Slightly higher Amazonian erosion rates are implied at Meridiani Planum (and other exhumed Noachian layered rocks on Mars [13]). Geologic mapping relations and the frequency of a population of old degraded craters >1 km diameter, clearly show the Meridiani Planum layered rocks to be Late Noachian in age [6, 14], yet the population of relatively fresh craters on the basaltic sand sheet is much younger, indicating that the entire record of Hesperian craters has been erased. The loss of Hesperian craters suggests at least order 10 m erosion since the Early Hesperian (~3.6 Ga [10]) or >3 nm/yr at Meridiani Planum. These erosion rates are comparable with those derived from the observed erosion and modification of young craters and ejecta by the Meridiani sands. Craters such as Eagle, Endurance and Vostok appear modified with sand filled centers and no ejecta, suggesting erosion of >1 m and <10 m, yielding >3 nm/yr and <30 nm/yr erosion rates during the Late Amazonian or since ~400 Ma [10]. Finally, slightly lower erosion rates (~1 nm/yr) result from the

concentration of hematite rich spherules in the upper 1 cm of the sand, which were derived from erosion of ~3 m of the sulfate outcrops [15] in the Amazonian.

Long term average erosion rates this low indicate a dry and desiccating climate similar to today's for the past 3 Ga. An environment in which liquid water is not stable is in accord with the lack of chemical weathering indicated by exposures of basalt and olivine basalt throughout equatorial Mars and in the soils of Gusev and Meridiani (see discussion and references in [16]) and the observed pattern of crater gradation observed at Gusev and Meridiani, which shows no evidence for erosion by liquid water (expected in a wetter environment) [17].

By comparison, erosion rates estimated from changes in Noachian age crater distributions and shapes on Mars are 3-5 orders of magnitude higher [see references in 11] and comparable to slow denudation rates on the Earth (>5 B) that are dominated by liquid water [8, 9]. An estimate of the erosion rates applicable to Meridiani in the Late Noachian just prior to when the evaporites investigated by Opportunity were deposited is estimated at about 8 B from widespread denudation in western Arabia Terra [14]. These rates are 5 orders of magnitude higher than those estimated for the Hesperian and Amazonian cratered plains of Gusev and consistent with the wet and likely warm environment documented in Meridiani Planum during the Late Noachian. A wet environment in the Noachian is also indicated by the strong chemical and mineralogic evidence for aqueous processing of the older rocks of the Columbia Hills at Gusev [18]. The erosion rates from the younger Amazonian Gusev and Meridiani plains as well as those from Viking 1 and Pathfinder strongly limit this warmer and wetter period to the Noachian, pre-3.7 Ga and a dry and desiccating climate since.

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